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AN EXPERIMENTAL STUDY OF SUPPRESSION OF OBSTRUCTED GAS WELL BLOWOUT FIRES USING WATER SPRAYS

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Center for Fire Research

By

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ABSTRACT

Gas well blowouts and fires continue to be one of the greatest dangers faced by the oil and gas production industry in exploring for new reserves. Each year there is significant loss of life, environmental damage, and destruction of expensive equipment resulting from blowouts. Previous experimental work done under the sponsorship of the Center for Fire Research, National Bureau of Standards has shown that the use of water sprays for extinguishing or suppressing gas well fires has significant promise. Fires of up to 18 MMSCF/D have been successfully extinguished with only about 130 gal/min water flow rate, which is equivalent to a water/hydrocarbon mass ratio of about 2.

In this study, this previous work was extended to higher gas flow rates (up to 35 MMSCF/D) and the effect of an obstruction above the fire was examined. Fires on drilling rigs will almost always have obstructions present in the burn area. It was found that the presence of an obstruction reduced the efficiency of the water spray extinguishment process. It is believed that an obstruction increases air/gas mixing while at the same time it decreases water/gas mixing.

For a simple I-beam obstruction located directly above flame, the water requirements doubled for low gas rates of about 5 MMSCF/D. However, as the gas flow rate increased, the effect of the obstruction on the required water rate was diminished. For a gas flow rate of 13 MMSCF/D,

the water requirement was only about one third more than for an unobstructed fire.

Extinguishment tests were also conducted with a square platform located above the fire. Extremely high water requirements were observed for this case. A relatively small scale fire, 2 MMSCF/D, required more than 30 lbs. of water per pound of hydrocarbon gas for extinguishment.

1. INTRODUCTION

The blowout and subsequent fire of a gas well is perhaps the most serious of all possible accidents for offshore oil and gas operations. These fires, characterized by a high momentum jet flame, endanger rig personnel, the environment, and equipment. Once a blowout has occurred, the only practical method to control the well is by shutting off the hydrocarbon flow--"capping" the well. However, if the blowout has ignited, a much more serious situation is encountered. Well blowout fires normally create extensive high heat radiation hazard zones in which it is dangerous and sometimes prohibitive for personnel to approach in the fire control process. This high heat radiation can damage the well control equipment to an extent that it can no longer perform the necessary well control functions.

Little data are available that predict the quantitative effect of water sprayed into the fire zone of a full scale well fire. It is known that radiation from flames is greatly reduced with the addition of relatively small quantities of water and extinguishment can be attained with larger amounts of water. Previous experimental work supported by the Center for Fire Research, National Bureau of Standards[1,2,3] shows significant promise in laboratory scale and medium scale experiments using water sprays to reduce flame radiation and extinguish the flame.

In this study, this previous work was extended to larger fires (35 MMSCF/D) and the effect of an obstruction in the flame area was studied. Obstructions are usually present in blowout fires and it is believed that this may cause improved mixing of air and hydrocarbon gas. A significant reduction in the efficiency of the water spray was observed when an obstruction was present.

A blowout through the drill string will generally result in the flames being limited to the above-drill floor area in the derrick. Control of this type of fire might be achieved with a spray system from which water is injected into the flames from external discharge positions, as shown in figure 1. The feasibility of this concept depends primarily on whether the estimated amount of water necessary for suppression/extinguishment is within the available pumping power of the facility. For scaling considerations, the variable chosen to represent the amount of water is the ratio of the mass flow rate of water to that of the gas, $\dot{m}_{H_2O}/\dot{m}_{gas}$[2]. The previous work[1,2,3] has indicated that a water/hydrocarbon gas mass ratio of about 2 is sufficient to extinguish an unobstructed 18 MMSCF/D fire. The effect of the structural members of a derrick on the water/hydrocarbon ratio required for extinguishment has not yet been determined.

This study did not address a variety of spray geometries and orientations nor did it involve any temperature profile measurements. It was felt that work done in previous studies[1,2,3] had adequately addressed these parameters. Instead, this study focused primarily on determining water/gas mass ratios for larger fires and for fires with one of two different obstructions present. The two obstructions studied were a 4 in. I-beam and a 55 in. square platform. Taking data for these simple obstruction geometries was felt to be a first step in understanding the

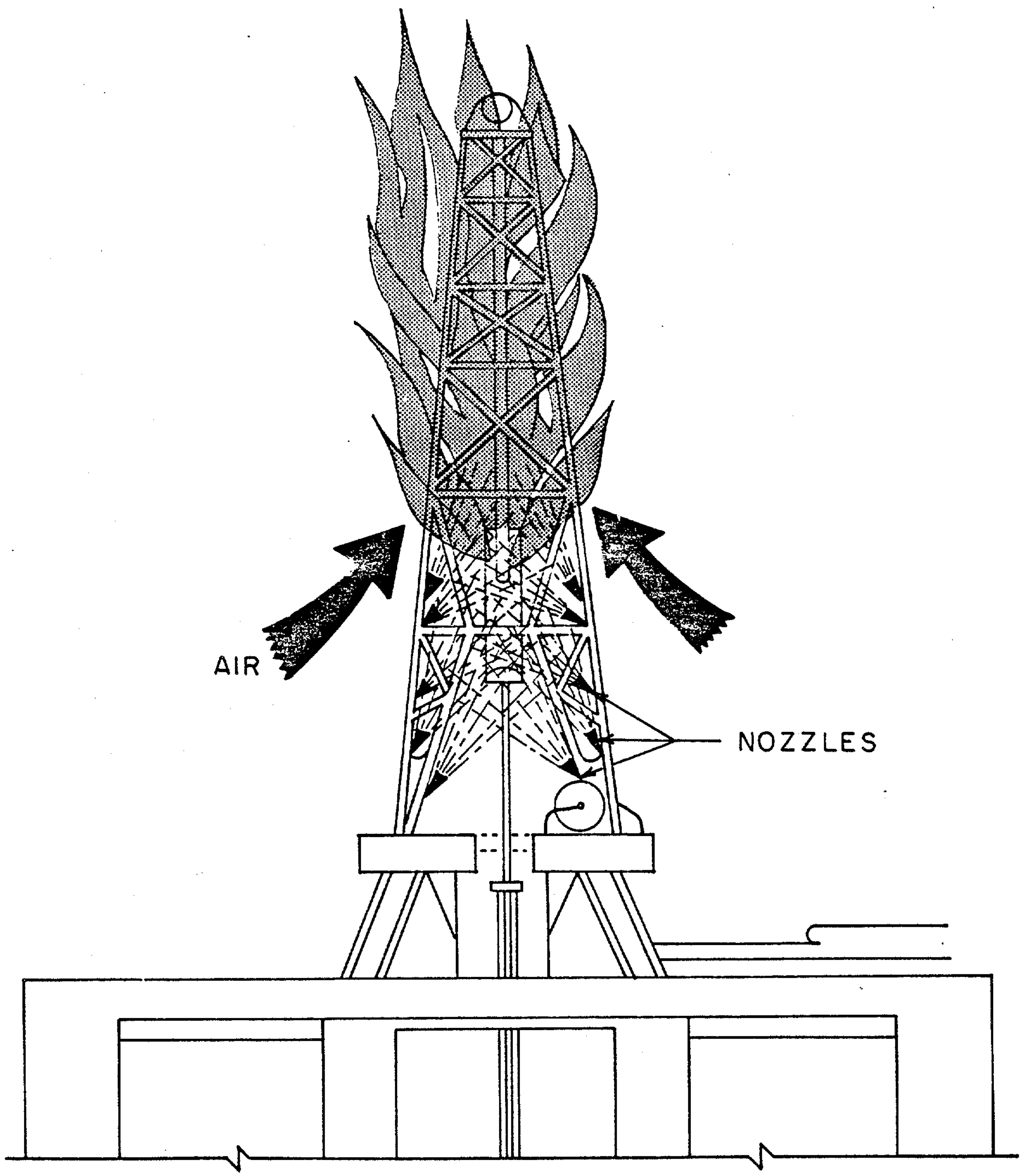

Figure 1. Fire Suppression System for Drill String Blowout Fires

more complex obstruction geometries present during the early stages of a rig site fire.

2. PREVIOUS OBSERVATIONS

It is believed that the actual mechanisms for flame extinguishment can be divided into four categories. These categories are interrelated and, quite often, extinguishment is due to a combination of more than one of these mechanisms. The first of these is referred to as flame blowoff. It is encountered when the gas exit velocity exceeds the maximum burning velocity of the gas and combustion is no longer possible. A second mechanism for extinguishment is by dilution of the fuel gas with a non-combustible additive. If sufficient amounts of this diluent are added until the oxidizing agent is displaced by the diluent, the fire will go out. The third mechanism is referred to as the cooling effect. This is accomplished with a water spray system in which the spray reduces the temperature of the flame below the minimum temperature necessary for combustion. It is believed that this mechanism is more accurately an early stage of dilution where the water droplets are converted to steam which acts as a diluent to extinguish the fire. The fourth mechanism of extinguishment, which is widely used in wild well control, results from the application of an explosive charge set near the actual blowout. This charge results in a pressure wave of such magnitude that the flame is separated from the exit orifice and the flame goes out.

2.1 Blowoff

The phenomenon of blowoff is described as the exit gas flow velocity beyond which a flame can no longer be sustained for that incident orifice size. For gas velocities below the blowoff value, the flame exists as a stable lifted flame. As the velocity is increased, the lift-off distance, the distance between the exit orifice and the base of visible luminosity of the flame, appears to become too great for continued self-sustaining combustion and the flame is gone. This occurs without the addition of any water or other diluent. The gas flow velocity appears to exceed a burning velocity everywhere.[2] A considerable amount of research has been conducted to determine these blowoff points by McCaffrey and Evans[5] and the results are summarized in figure 2. It should be noted that for diameters greater than approximately 42 mm, the flame cannot be blown off regardless of how high the gas exit velocity is. This is indicative of the theory that blowoff manifests itself in the smaller orifice size diameters (below 41 mm). It is also interesting to note that for a small orifice size the flame first blows off but as stagnation pressure is increased it can be reignited when it reaches the top portion of the curve. It becomes clear that blowoff is not as significant a mechanism in large blowout fires due to the fact that it requires a relatively small diameter for extinguishment, or more accurately, non-ignition.

2.2 Dilution

A more applicable mechanism of extinguishment for gas well blowout fires might be by dilution. Dilution occurs when a non-participating

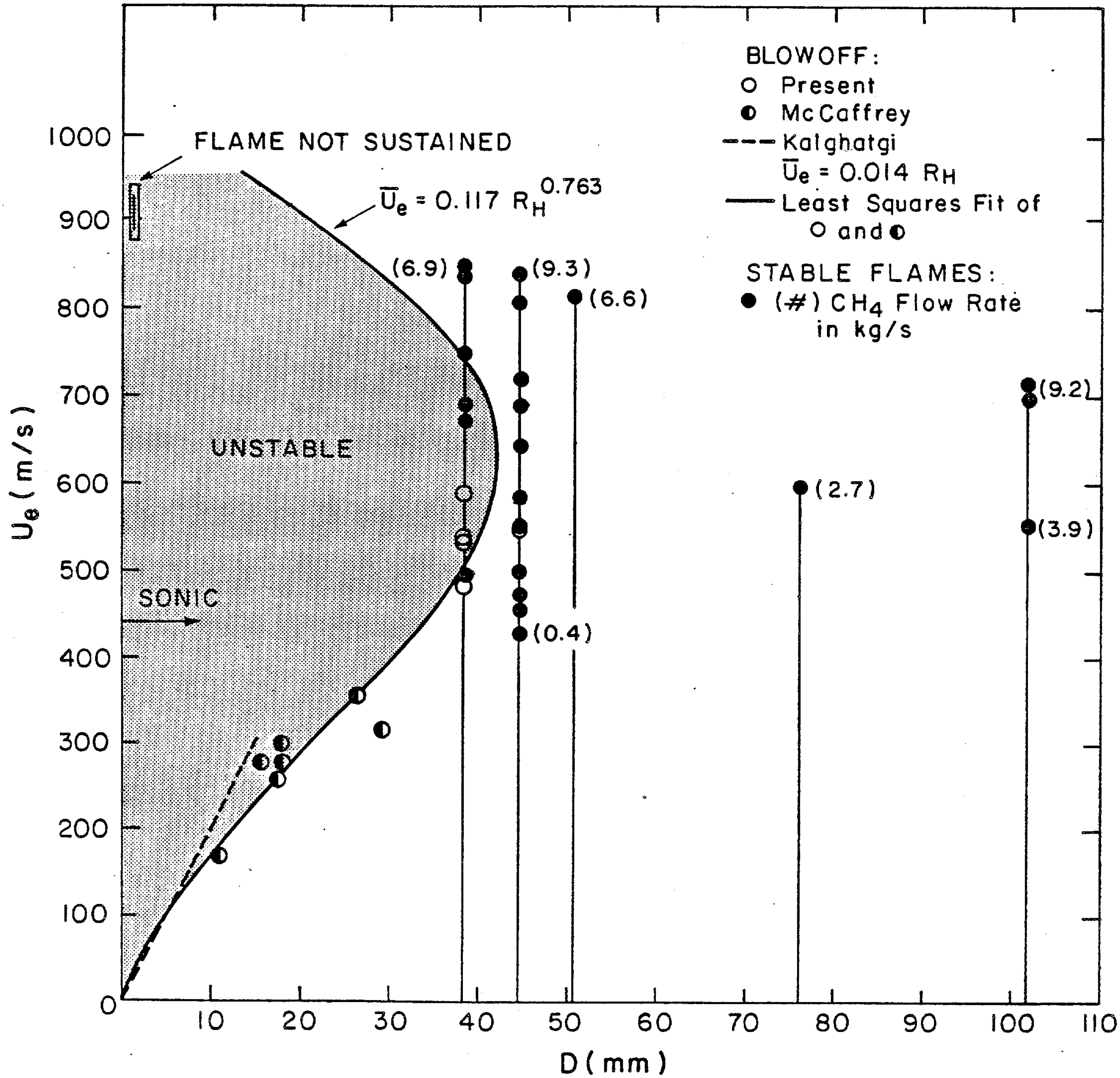

Figure 2. Summary of Blowoff Points for CH_4

gas, or diluent, is carried along with the gas and is heated in the process, which extracts energy from the flame resulting in a lower flame temperature. The diluent could also take the place of oxygen in the entrainment process thereby lowering the combustion efficiency.[2] Earlier work done by Gupta[6] generated interesting results on the use of steam and argon as diluents when mixed with propane prior to burning. The resulting radiative fraction is decreased with the increased addition of diluent but only down to an apparently finite radiative reduction value (.4 - .5) before extinguishment. The results of these tests, including the addition of water sprays, are summarized in figure 3. Another major area of interest concerning the addition of a diluent is in the use of carbon dioxide. Carbon dioxide extinguishes fire by reducing the concentrations of oxygen, the vapor phase of the fuel, or both in the air to the point where combustion stops.[7] Carbon dioxide has long been accepted as an effective means of extinguishment by the fire protection industry and its application for extinguishment by dilution of blowout fires has been studied. Of equal importance in their use as diluents are the halogenated hydrocarbons. Halogenated hydrocarbons, such as Halon 1301 (CF_3Br), are known to be highly effective in quenching the flames of hydrocarbon fuels in air.[4] The mechanism by which Halon 1301 extinguishes fires is not completely understood, but it appears to involve a chemical inhibition of the combustion reaction. Halon 1301 has also been regarded as a "chain breaking" agent, meaning that it acts to break the chain reaction of the combustion process.[7] Little quantitative data are available concerning the effectiveness of halons on large scale blowout fires.

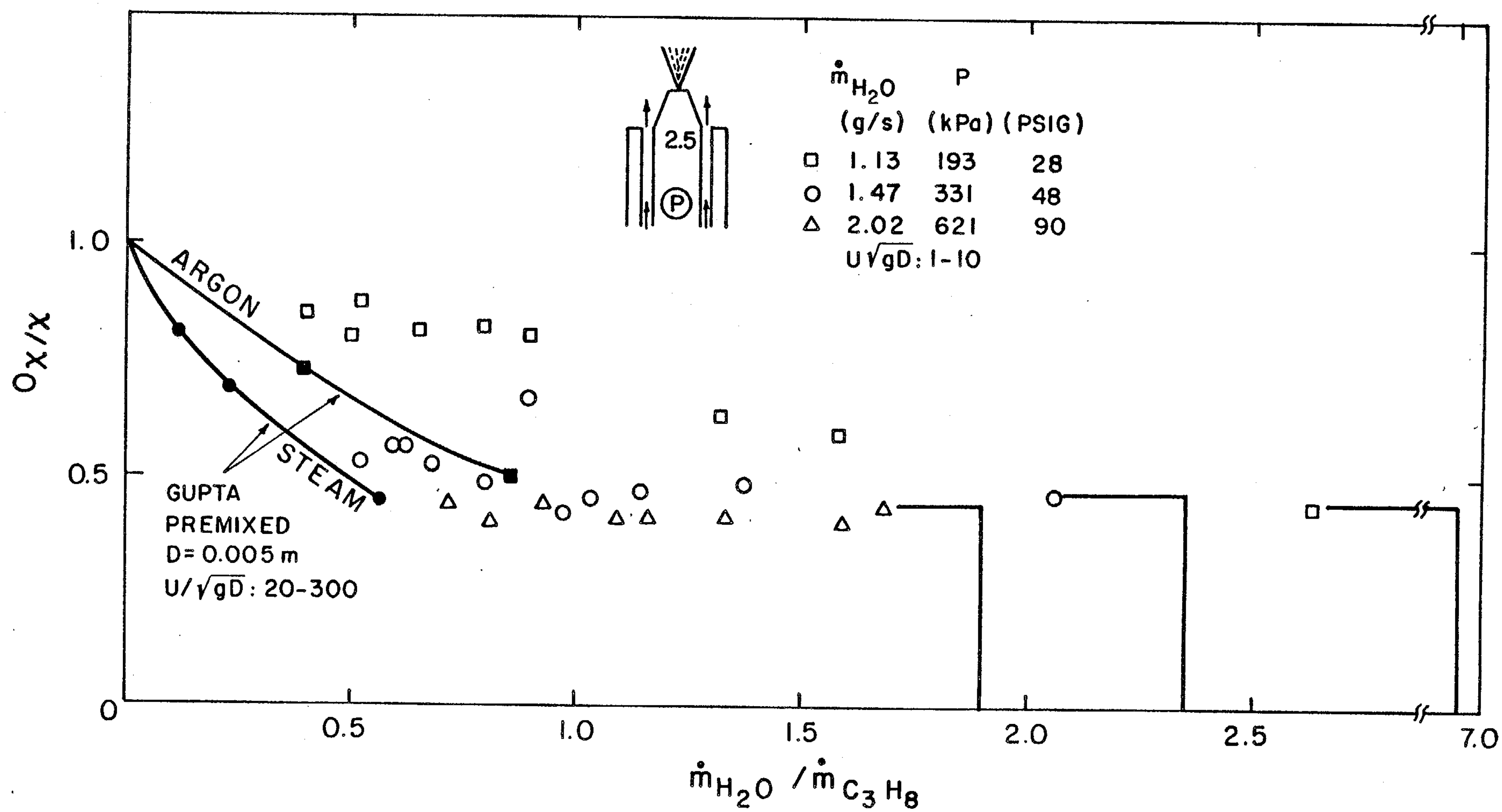

Figure 3. Radiative Fraction Reduction Due to Addition of a Diluent

The feasibility of any dilution system should consider the possibility of the toxicity of the diluent(s) in addition to the relative effectiveness, cost, and availability. The question of toxicity may be an important parameter as an increased concentration is required for larger fuel gas rates in actual blowout fires.

When a diluent is internally injected into the gas flow, it directly affects the flammability limits of the resulting flow. To what degree it affects it depends on the ratio of the inert gas, or diluent, to flammable gas and also on the properties of both the inert and flammable gases. Figure 4 illustrates the effect of CO_2 and N_2 on the flammability limits of CH_4, CO, and H_2 from previous work performed by Coward, et. al.[8] Note that for an inert-to-flammable gas ratio of 3.2 for the CH_4 + CO_2 mixture, the flammability limits of the mixture have been exceeded and no combustion should occur. The ratio of 3.2 by volume is equal to an 8.8 mass ratio. It is important to point out that these limits of flammability are for ideal mixing and hence, internal injection in a fire suppression system.

2.3 Cooling

The third mechanism will be referred to as cooling although it generally involves the combination of radiative reduction as well as heat transfer to a diluent before extinguishment. The cooling of combustion products within the flame has been investigated using both interior injection and exterior injection of water spray mixed with the flow. The effect of external sprays on CH_4 diffusion flames has been studied

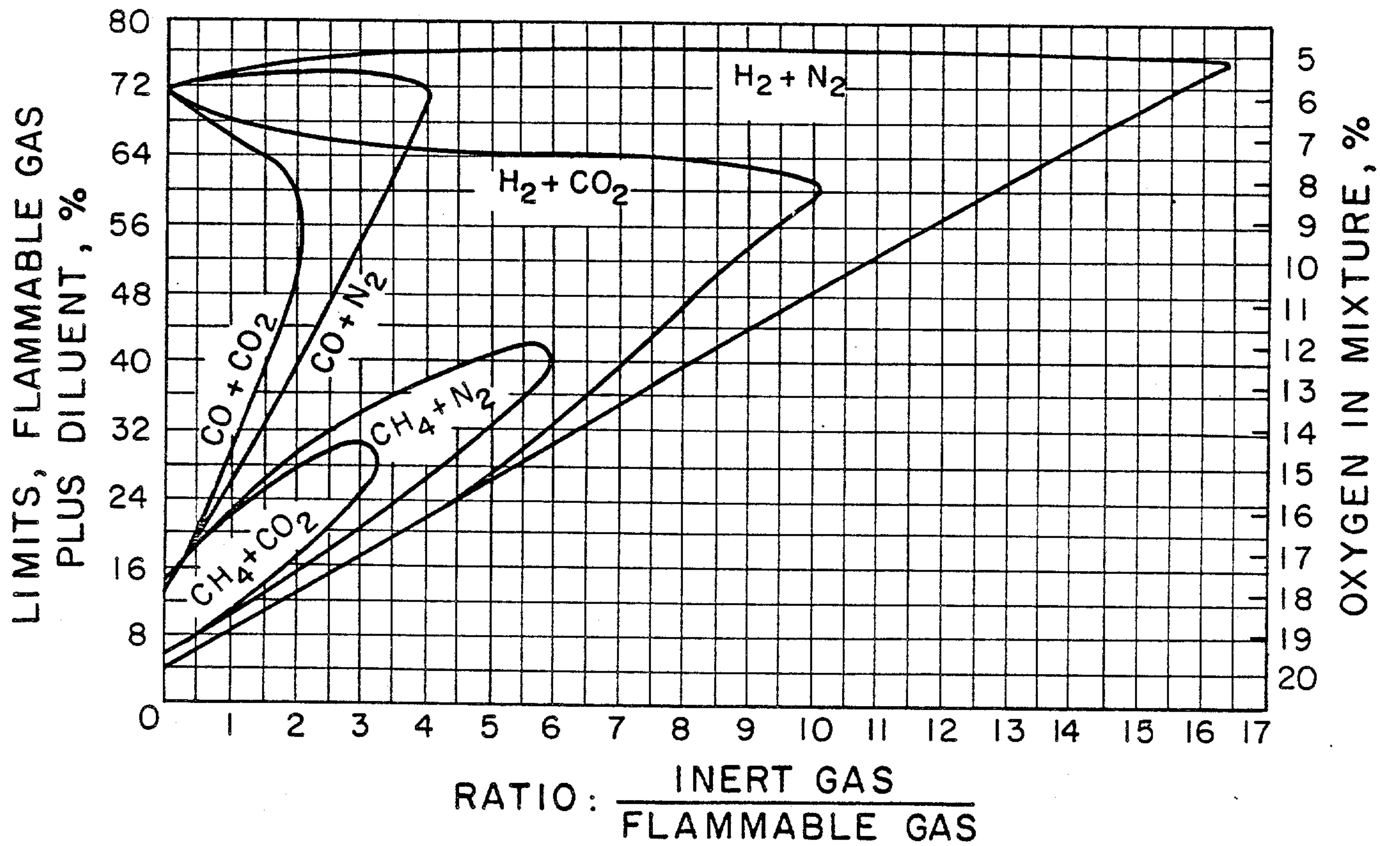

Figure 4. Limits of Flammability of Hydrogen, Carbon Monoxide, and Methane Containing Various Amounts of Carbon Dioxide and Nitrogen after Coward et. al.[8]

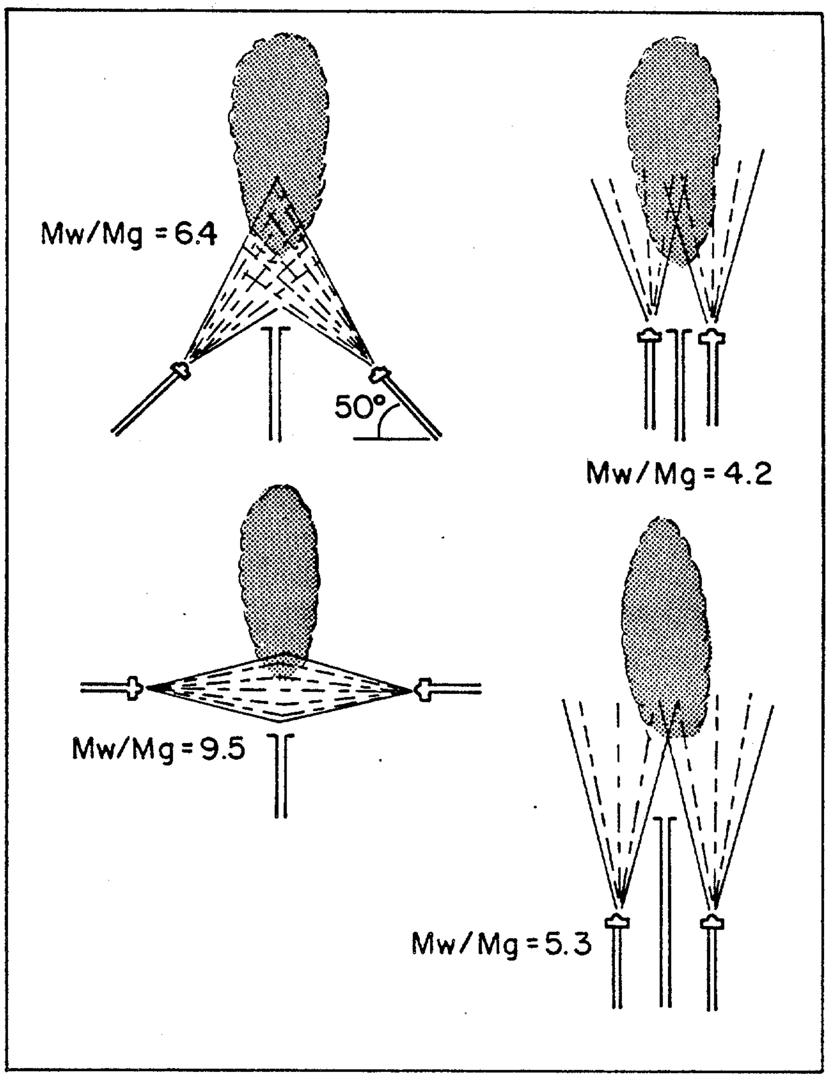

Figure 5. Relative Effectiveness of Various Water Spray Geometries

by Evans and Pfenning[1] using small scale flames and the most effective spray geometry was determined. Several spray geometries and nozzle types were tested, with the most efficient consisting of a nozzle system spraying vertically parallel to the flame axis. The relative effectiveness of several spray geometries are illustrated in figure 5. Some preliminary work[2,3] using internal injection of the water spray on small scale fires gave good results for decreasing flame temperatures and extinguishment. This was much as expected due to the fact that most, if not all, of the water is allowed to reach or be entrained into the combustible region. The temperature reduction was nearly twice as great when compared to similar external water sprays for the lower part of the flame (Figure 6). However, it is estimated that temperature reductions possible with internal sprays would still not be sufficient to prevent loss in material strength of steel structures and additional water sprays would be necessary. Also, the use of internal injection would pose a significant problem for applications to blowout fires due to complications of design. A comparison of full-scaled tests using both internal and external injection was done by Evans and Pfenning[1] and the results are illustrated in Table 1.

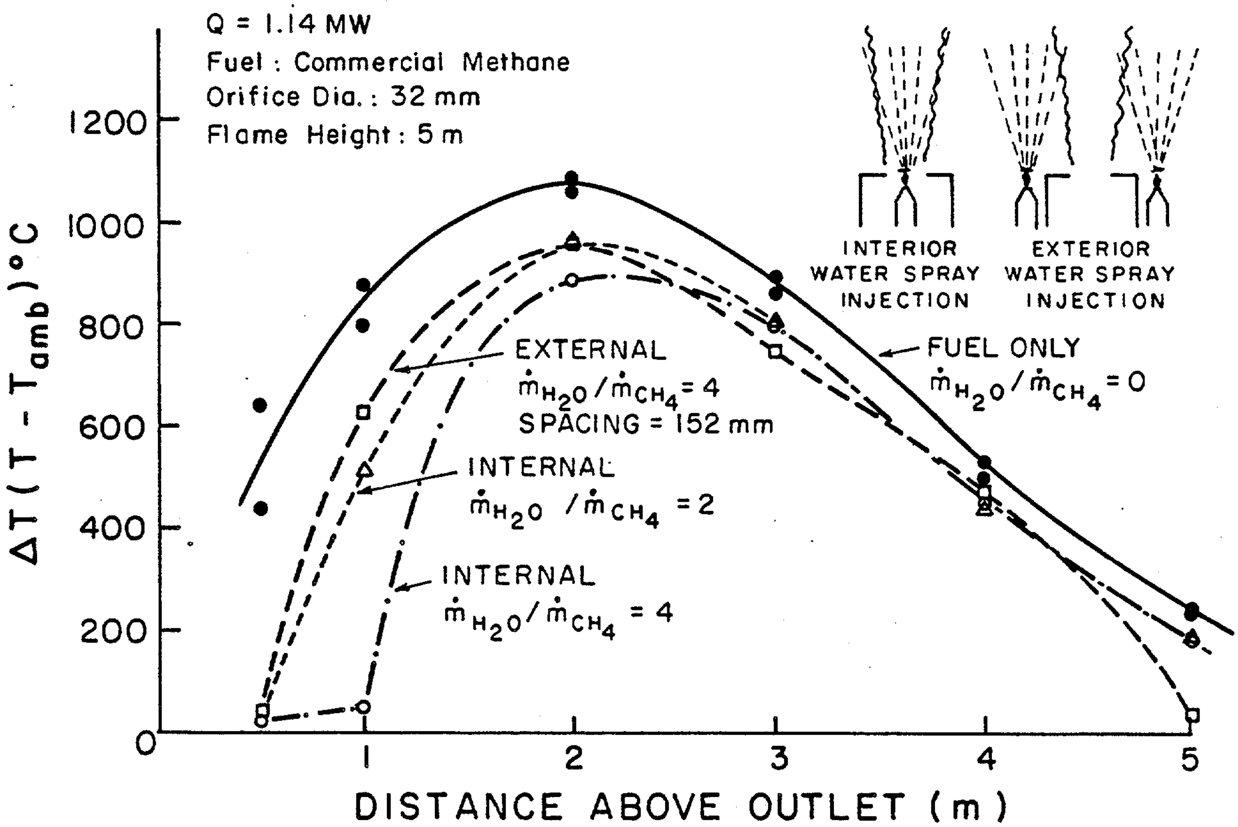

Figure 6. Temperature Rise on the Axis of the Jet Flame

TABLE 1. Summary of Data for Both Internal and External Water Sprays

Gas and water flow rates

Rates	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Injection location of water	Internal	Internal	Internal	External	External	External	Internal
Gas flow rate, cfs	138	220	212	196	192	178	150
Heat release rate, MW (complete combustion)	144	230	222	205	201	186	157
Water flow rate, gpm	25.4*	33.3	51.4	258	129	86.1	
Water flow rate/gas flow rate mass ratio	0.59	0.50	0.920	4.26	2.17	1.56	--
Average wind speed, mph	3.4 (σ=0.5)	3.5 (σ=0.6)	3.5 (σ=0.04)	0.9 (σ=0.15)	0.8 (σ=0.24)	1.3 (σ=0.17)	1.8 (σ=0.05)
Extinguished	yes†	no	no	yes	yes	no	--

*Approximation

†Flame tilted off axis by wind prior to water spray injection.

3. EXPERIMENTAL TEST PROGRAM

The experimental test program was conducted at the LSU Blowout Prevention Research and Training Well Facility located on the LSU campus in Baton Rouge. This facility is centered around two 6,000 ft. wells used to simulate threatened blowout situations in both a surface and in a subsea environment for research and training purposes. Included in the facility are a high pressure well control choke manifold, drilling fluid storage and processing equipment, high pressure mud pumps, and a computerized instrumentation and control center. A special test wellhead was constructed to do the fire suppression experiments needed for this study.

3.1 Experimental Apparatus

A layout diagram for the facility is shown in figure 7. A flow schematic is shown in figure 8. The control room was used for remote operation of gas rates, pump speed for water spray and monitoring of all pertinent data. Natural gas was supplied via a 6 in. pipeline about 0.3 mi. long which tapped into a natural gas trunk line. The 6 in. line was metered and regulated (figure 9) with the gas rate set points being adjusted remotely in the control room. The gas rate was monitored by a microprocessor which made adjustments on a flow control valve to maintain the set point regardless of changes in static pressure and temperature. The composition of the natural gas used in the experiments is shown in Appendix A.

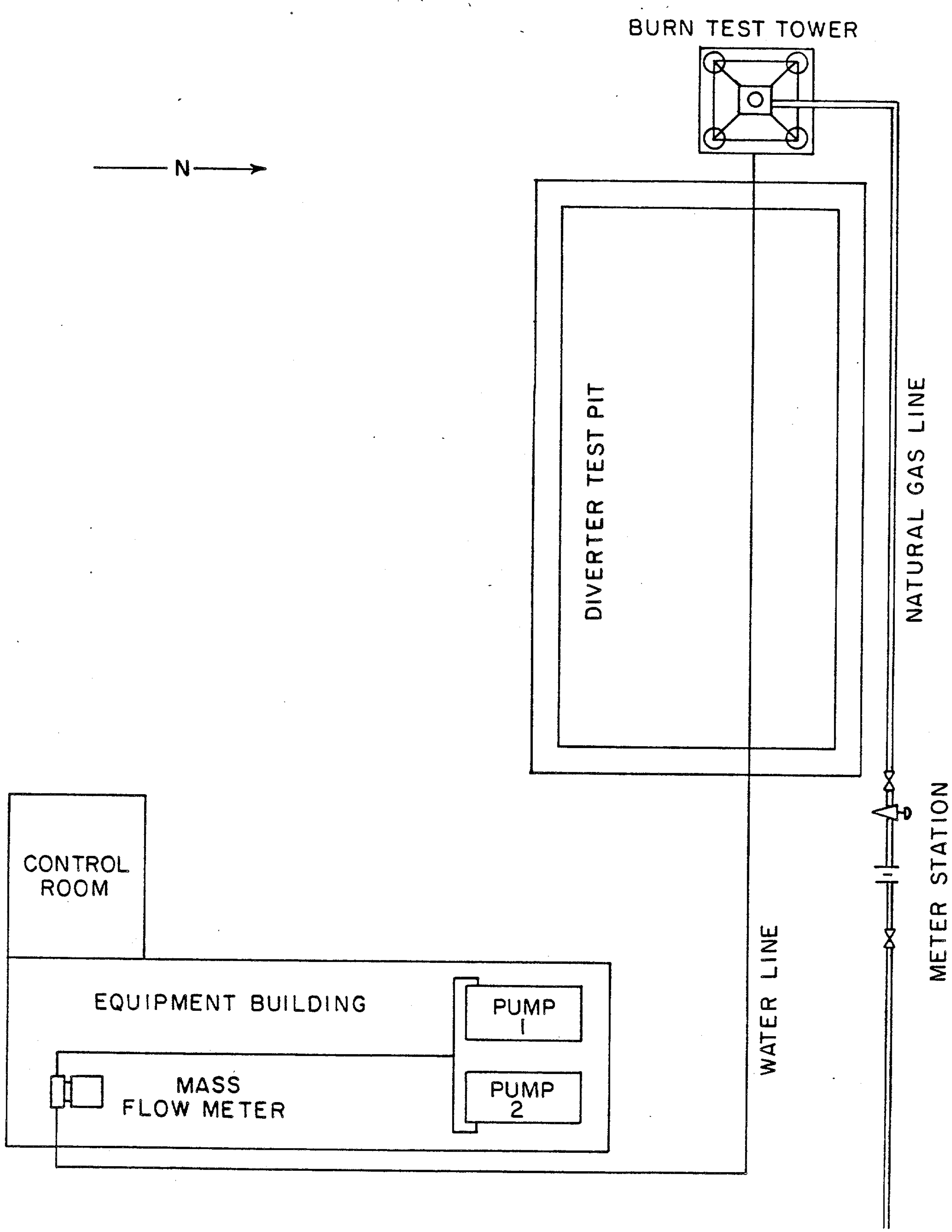

Figure 7. Layout Diagram for Experimental Apparatus

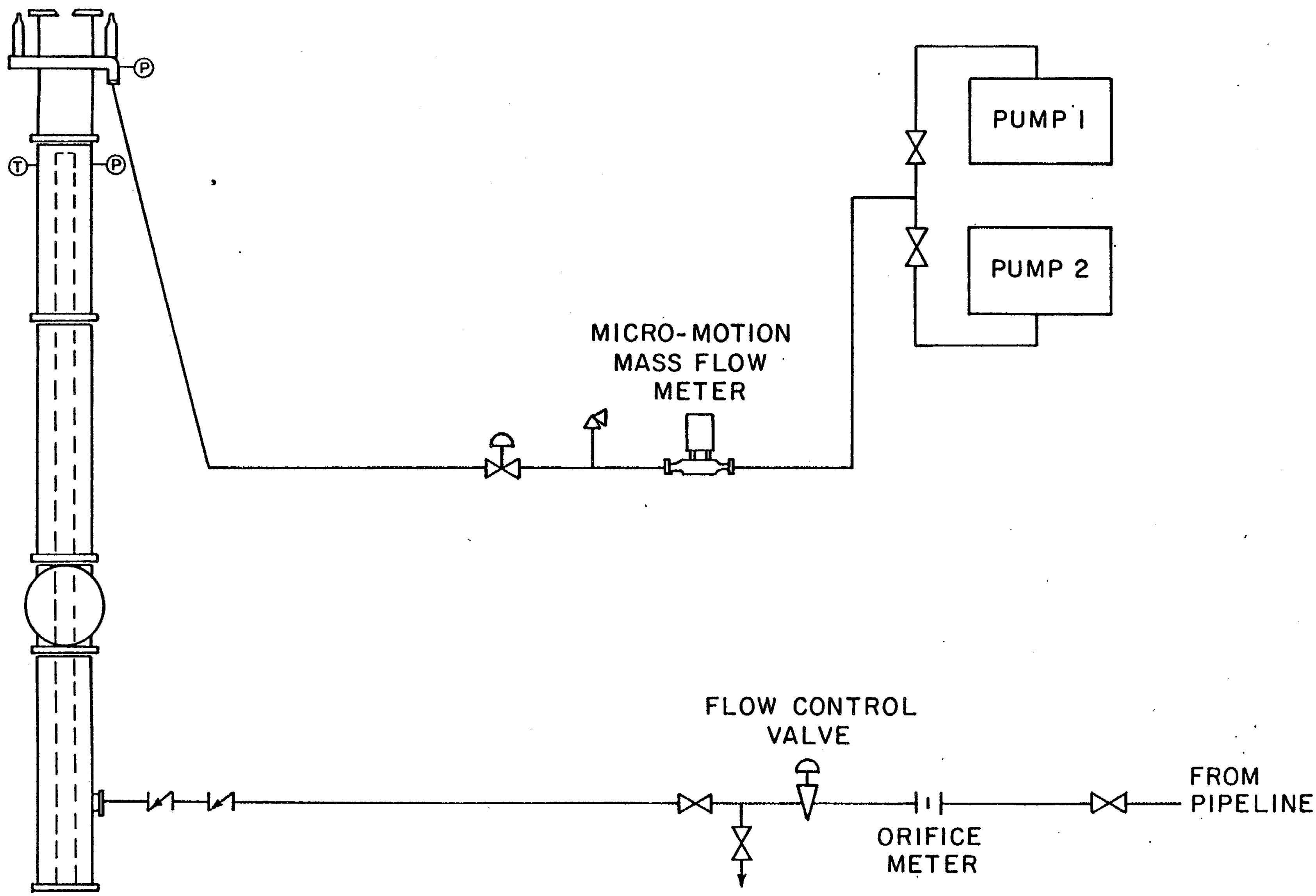

Figure 8. Flow Schematic of Experimental Apparatus

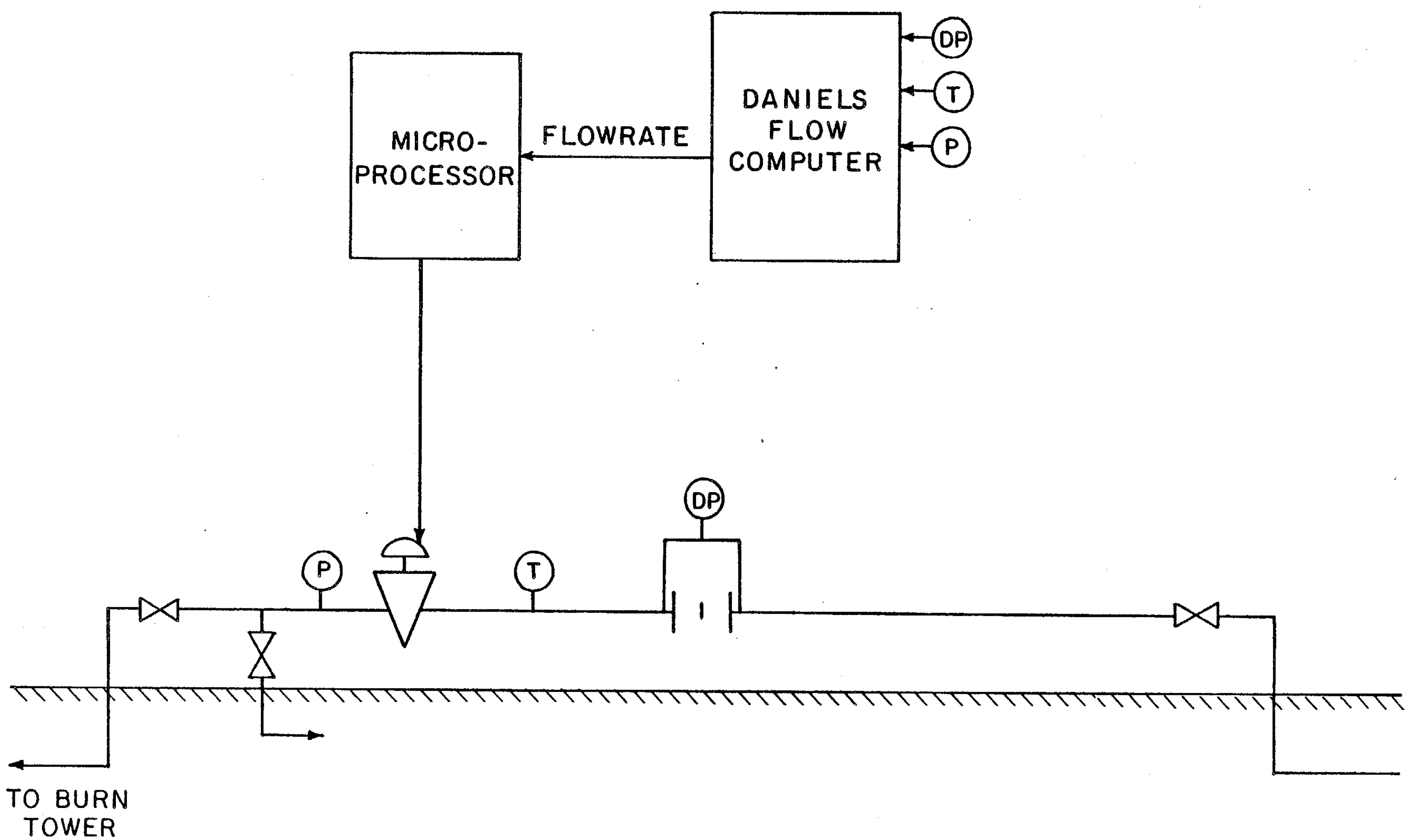

Figure 9. Schematic of Gas Meter Station

The water for the experiments was stored in several compartments of four 150 bbl. tanks and it was delivered to the nozzles by the use of two Halliburton cementing pumps each capable of delivering approximately 175 gpm. The water flow was routed through a Micro-Motion mass flow meter for more accurate water flow rate measurements.

The test wellhead was supported by a 40 ft. derrick, with the wellhead projecting through the top of the derrick. A Shaffer annular preventer was initially in place from previous experiments and was left in the stack in the open position. The casing was constructed using 8.725 in. O.D. pipe. A schematic showing the main features of the test wellhead is given in figure 10.

For some experiments, one of two obstructions was attached above the wellhead exit. The first obstruction tested consisted of a single I-beam obstruction placed directly above the flame exit (figure 11). The second obstruction consisted of a 55 inch square platform which was also placed over the gas exit. Details of this configuration are given in figure 12. Obstructions above a rig fire could be caused by the traveling block, the derrick, or the rig floor itself, depending upon the equipment arrangement in place at the time of the fire and the location of the pressure leak.

The top assembly of the test derrick consisted of the water spray nozzle and the orifice plate at the exit as shown in figure 13. The spray system comprised 4 spray nozzles spatially located on a 3 in. water manifold. The nozzles were directed vertically upwards along the

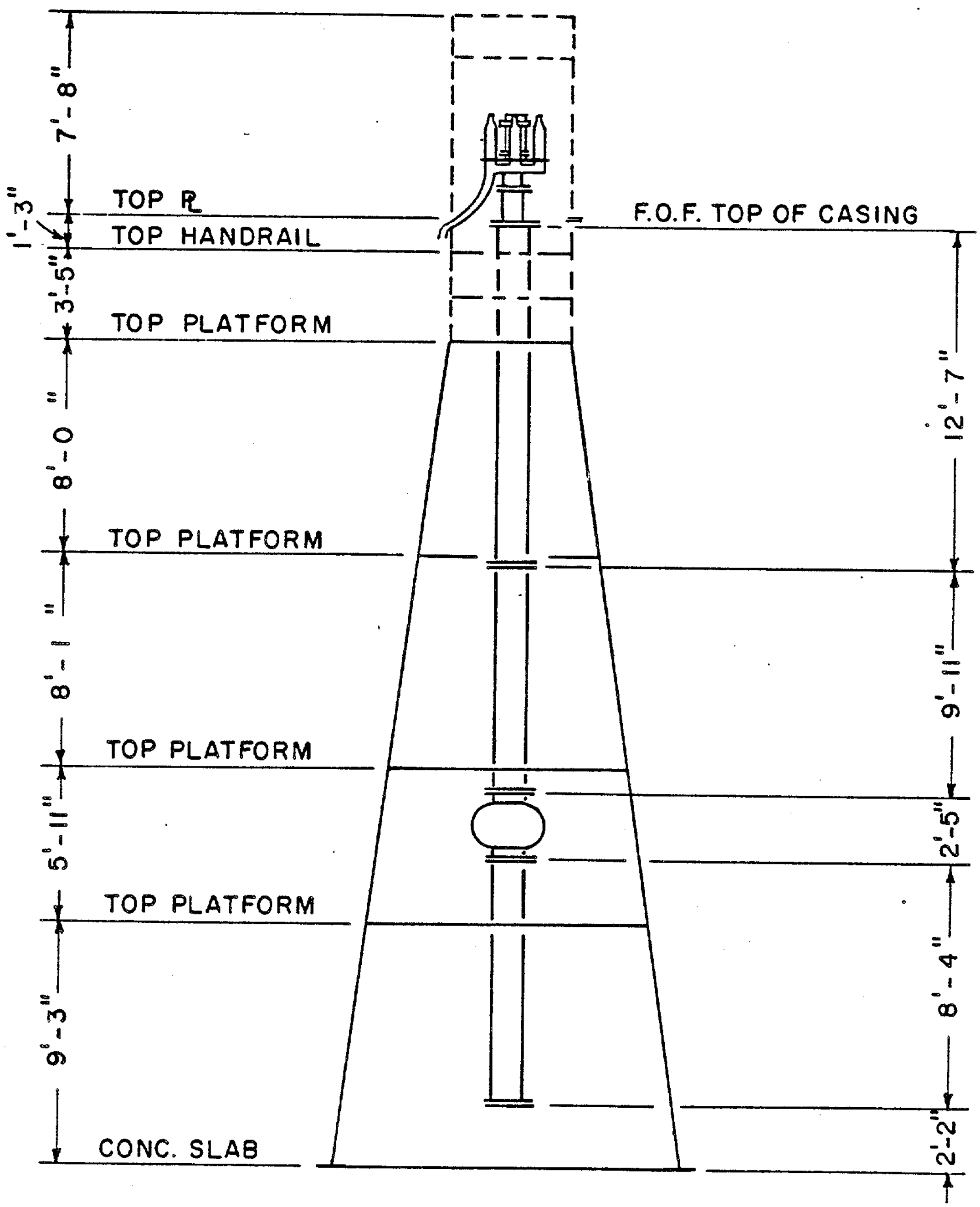

Figure 10. Experimental Test Wellhead

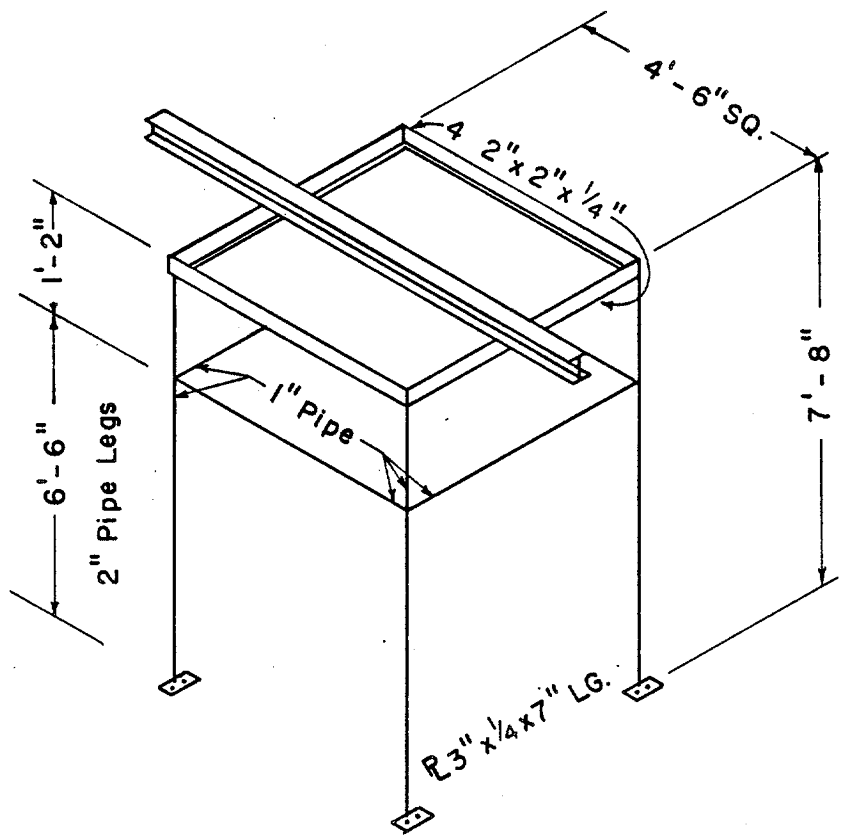

Figure 11. 4 inch I-Beam Obstruction

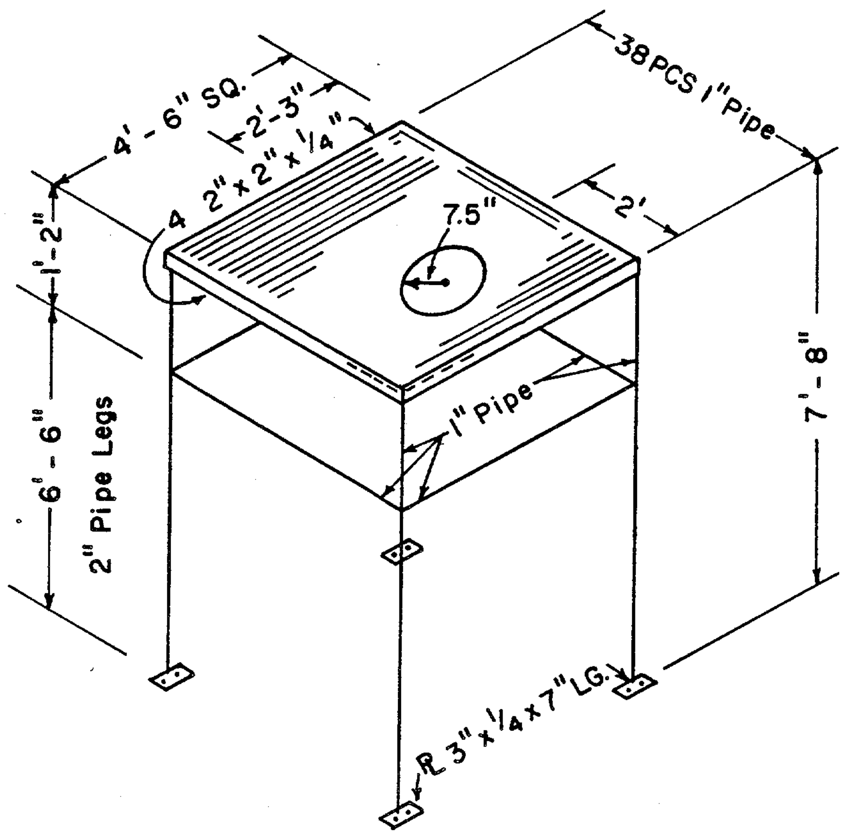

Figure 12. 54 inch Square Platform Obstruction

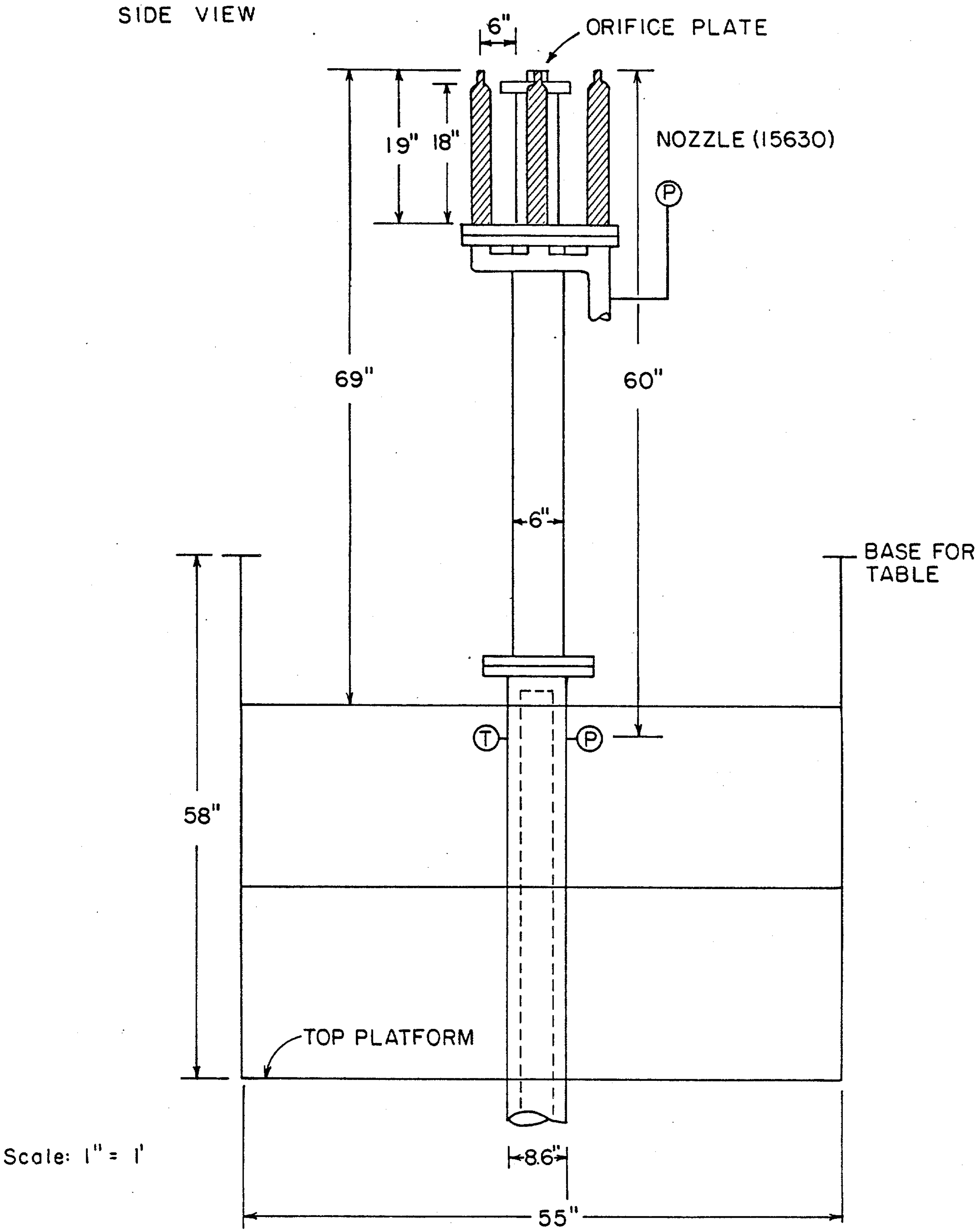

Figure 13. Top Assembly of Burn Tower

axis of the gas flow. The nozzles' specifications were designated as 15° full cone spray nozzles with 2 in. connections and listed as 15630. The water manifold was then connected, through the use of swivels, to the supply line from the pumps. The orifice plate was bolted directly on top with a 4 in. opening for the water spray tests.

The test derrick was outfitted with various instruments to record the pertinent parameters. The gas temperature and static gas pressure were measured at a distance of 5 ft. below the orifice exit and the nozzle pressure was taken at a point 12 in. below the nozzle exit. These sensors, in addition to the water flow rate and gas flow rate, were recorded on a 6 pen chart recorder located in the control room. For several of the water spray tests, the radiative fraction was monitored using two radiometers mounted at the top of the derrick and their output was recorded on a separate 2 pen chart recorder.

3.2 Experimental Procedure

The primary focus of the research was aimed at determining the required mass ratios for extinguishment at higher gas flow rates for both the unobstructed case as well as the case with an obstruction as described above. Several preliminary runs were made to determine lift-off heights and flame blowoff data and the procedures followed to obtain that will be given also.

The experimental procedure for the blowoff tests proceeded as follows. First, the gas flow is initiated and the flame is ignited, then the ignitor system is turned off. Secondly, the gas rate is increased to a range below the expected blowoff rate based on either audible indications or theory. Next, the rate is further increased in small increments through the possible range of blowoff being careful not to jump across the blowoff region to the supersonic velocity where flame stability returns again. If blowoff occurs, the event marker is activated on the chart recorder in the control room, which records the condition of all affecting parameters at the time of blowoff. Finally the gas flow is shut off and the static pressure is again allowed to stabilize for the next test run.

The procedure followed for the water spray tests was similar to the procedures used for blowoff determination. The ignitor is turned on and the desired gas rate is selected and input into the flow controller. The flow controller automatically begins to bring the gas rate up to the setpoint and maintains this position. Next, the water spray is initiated by opening a pneumatic valve downstream of the water flow meter. The pump speed is gradually increased and the parameters are monitored from the strip chart recordings. When the first visible indication of extinguishment occurs, an event marker is tripped on the chart recorders and both the gas rate and water rate are brought back to zero. The gas pipeline pressure and water volume are allowed to build up again for the next test run.

3.3 Experimental Test Matrix

The test matrix for blowoff consisted only of determining the blowoff rates for 3 different orifice sizes. These sizes were listed as a 4 in., a 1.75 in., and a 1.5 in. orifice. Each orifice was installed and tested up to the point of determining the blowoff rate, if any, and repeating the rates for confirmation. The various data points recorded were for each stable step in the determination of the blowoff rate.

The test matrix for the water spray extinguishment consisted of three basic groups of tests: unobstructed, 4 in. I-beam obstruction, and platform obstruction. The gas flow rate was varied for each group from 5 MMSCF/D to 35 MMSCF/D in increments of 5 and then repeated for accuracy. This schedule worked well for the unobstructed fires, but for the obstructed fires it became evident that a maximum gas rate is quickly exceeded due to the limited water supply and the schedule had to be shifted accordingly.

A typical strip chart record of the burn tests for an unobstructed fire is included in figure 14. Full scale for the parameters shown on this figure are as follows:

Water Flow Rate	(0-5000 lb/min)
Gas Stagnation Pressure	(0-1000 psig)
Flowing Gas Temperature	(0-200°F)
Water Pressure at Nozzles	(0-500 psig)
Pump Pressure	(0-5000 psig)
Gas Flow Rate	(0-50 MMSCF/D)

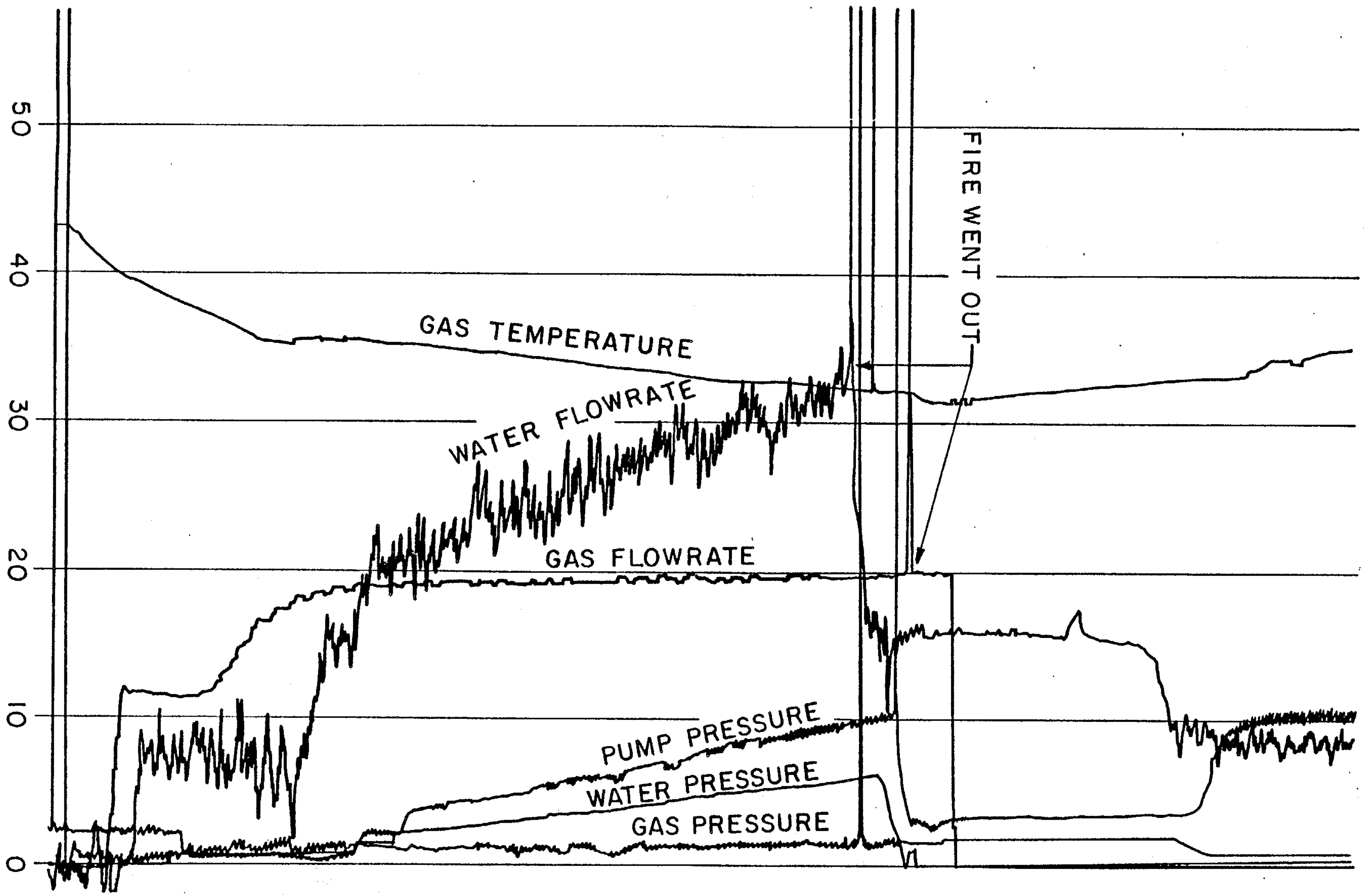

Figure 14. Typical Strip Chart Record of Water Rate, Gas Rate, Gas Temperature and Pressure, Nozzle Pressure, and Pump Pressure

4. RESULTS

In order to evaluate the potential applications of the water spray system as an effective means of fire suppression/extinguishment, approximately 50 experimental tests were run and about 75 data points were correlated. About 10 of these runs focused on the determination of blowoff while the remainder of the tests were directed at determining the amount of water required to extinguish a burning blowout either with or without an obstruction present.

4.1 Blowoff Results

The most advantageous situation with regards to a blowout fire would be, of course, self-extinguishment. Unfortunately, blowoff generally occurs naturally only for orifice diameters less than 1.75-in. in diameter. The importance of understanding and quantifying this mechanism is evident in the fact that a number of blowouts may have begun as small leaks with an exit velocity exceeding that of its burning velocity and thereby not being capable of combustion. It is for this reason that considerable energy was expended to further investigate this phenomenon. The results of the blowoff tests are given in table 2 and these results, combined with results obtained previously[5], are summarized graphically in figure 2.

4.2 Water Spray Results

A comparison of mass ratios for both the internal and external

TABLE 2. Experimental Data from Blowoff Rate Tests

D (in.)	GAS FLOW MMSCF /D	PRESS. psig	TEMP. DEG. F	RADIATION EAST (mv)	RADIATION WEST (mv)		GAS FLOW kg/s	PRESS. RATIO PR	MACH. NO.
4	37.7	120					9.1988	9.163	2.10
	37.6	100		9	8.5		9.1744	7.802	2.00
1.75	22.5	322	57	6.8	7.1		5.49	22.90	2.66
	38.3	480	57	6.5	6.9		9.3452	33.65	2.89
	20.2	265	57	5.91	5.7		4.9288	19.02	2.54
	2	18	70	2.2	2.13		0.488	2.224	1.15
	2.9	30	69	3.16	2.76		0.7076	3.040	1.39
	3.6	41	68	3.33	3.43		0.8784	3.789	1.54
	5.1	62	67	3.53	3.99		1.2444	5.217	1.75
	7.1	92	66	4.13	4.32		1.7324	7.258	1.96
	9.4	122	64	4.4	4.53		2.2936	9.299	2.11
	5	60	61				1.22	5.081	1.73
	2.7	28	62	2.9	2.95		0.6588	2.904	1.36
	3	30	66	3.15	3.05	***	0.732	3.030	1.39
	5.1	62	60	4.21	3.84		1.2444	5.217	1.75
	3.4	37	59	3.53	3.4		0.8296	3.517	1.49
	1.9	18	58	2.53	2.42		0.4636	2.224	1.15
	2.4	22	58	2.93	2.93		0.5856	2.496	1.24
	3.1	32	58	3.43	3.39		0.7564	3.176	1.42
	3.6	41	57	3.78	3.73		0.8784	3.789	1.54
	2.05	18	56	2.72	2.76		0.5002	2.224	1.15
1.5	26.9	470	71	6.68	7		6.5636	32.97	2.88
	2.3	39	75	2.86	2.5	***	0.5612	3.653	1.52
	28.2	455	67	6.05	6.73		6.8808	31.95	2.86
	6.5	93	66	3.7	4.54		1.586	7.326	1.97
	1.9	22	71	0.93	1.4		0.4636	2.496	1.24
	2.25	40	71	2.31	2.28		0.549	3.721	1.53
	4.8	78	71	3.18	3.1		1.1712	6.306	1.87
	8.6	151	71	4.12	4.12		2.0984	11.27	2.23
	1.85	27	71	2.62	2.38	***	0.4514	2.836	1.34
		28	71	2.42	2.93	***	0	2.904	1.36

*** BLOWOFF

spray arrangements in the large-scale work done by Evans[1] indicates an obvious advantage in efficiency of the internal sprays. However, an actual application of an internal spray system would prove to be considerably more difficult than for a simple external spray geometry. It is because of this reason that more interest has been focused on the external spray arrangement and, consequently, the bulk of this research was directed at obtaining data for this geometry. Two basic geometries were studied in the flame suppression studies. The first case was for a blowout in which there were no obstructions above the burning wellhead. This geometry is generally present in the later stages of a blowout when all of the rig debris has been removed from the burning wellhead. This geometry would also apply to some producing wellhead situations. The second case was a blowout in which an obstruction was present above the burning wellhead. This would generally be the case during the initial stages of an annular blowout on a drilling well. Two types of obstructions were studied, one being a 4 in. I-beam and the other a 55 in. square platform, to determine what effect the degree of obstructed flow area had on the required mass ratio for extinguishment.

4.2.1 Unobstructed Fire

Summarized in Table 3 are the results obtained by spraying various quantities of water into a high momentum jet diffusion natural gas flame of varying magnitudes. Gas flow rates in the range of 2-35 MMSCF/D were included in the study. The results of Table 3 have been displayed graphically in figure 15, in which the mass ratio of water to natural gas is plotted versus gas flow rate. Note that for gas rates above 26

TABLE 3. Extinguishment Tests Conducted for an Unobstructed Flame

Run No.	Gas Flow Rate (MMSCF/Day)	Extinguishment Water Flow Rate (lb/min)	Gas Exit Pressure (psig)	Gas Temperature (°F)	Water-Gas Mass Ratio
1	10.0	1660	17	63	5.1
2	16.6	2350	37	54	4.3*
3	9.5	1750	18	62	5.6
4	5.8	1200	8	61	6.3
5	20.0	1180	35	58	1.8
6	15.5	1100	38	57	2.2
7	18.6	1300	42	54	2.1
8	23.0	1150	55	53	1.5
9	19.2	2050	41	55	3.2*
10	17.5	1750	40	55	3.0*
11	19.5	1800	50	65	2.8*
12	25.5	2350	48	61	2.8*
13	25.6	2070	57	-	2.5
14	31.3	1700	75	-	1.7
15	9.2	1760	8	-	5.8
16	33.1	2050	82	-	1.9
17	9.4	1660	3	-	5.4
18	35.0	2100	8	-	1.8

*Significant wind velocity occurred during test.

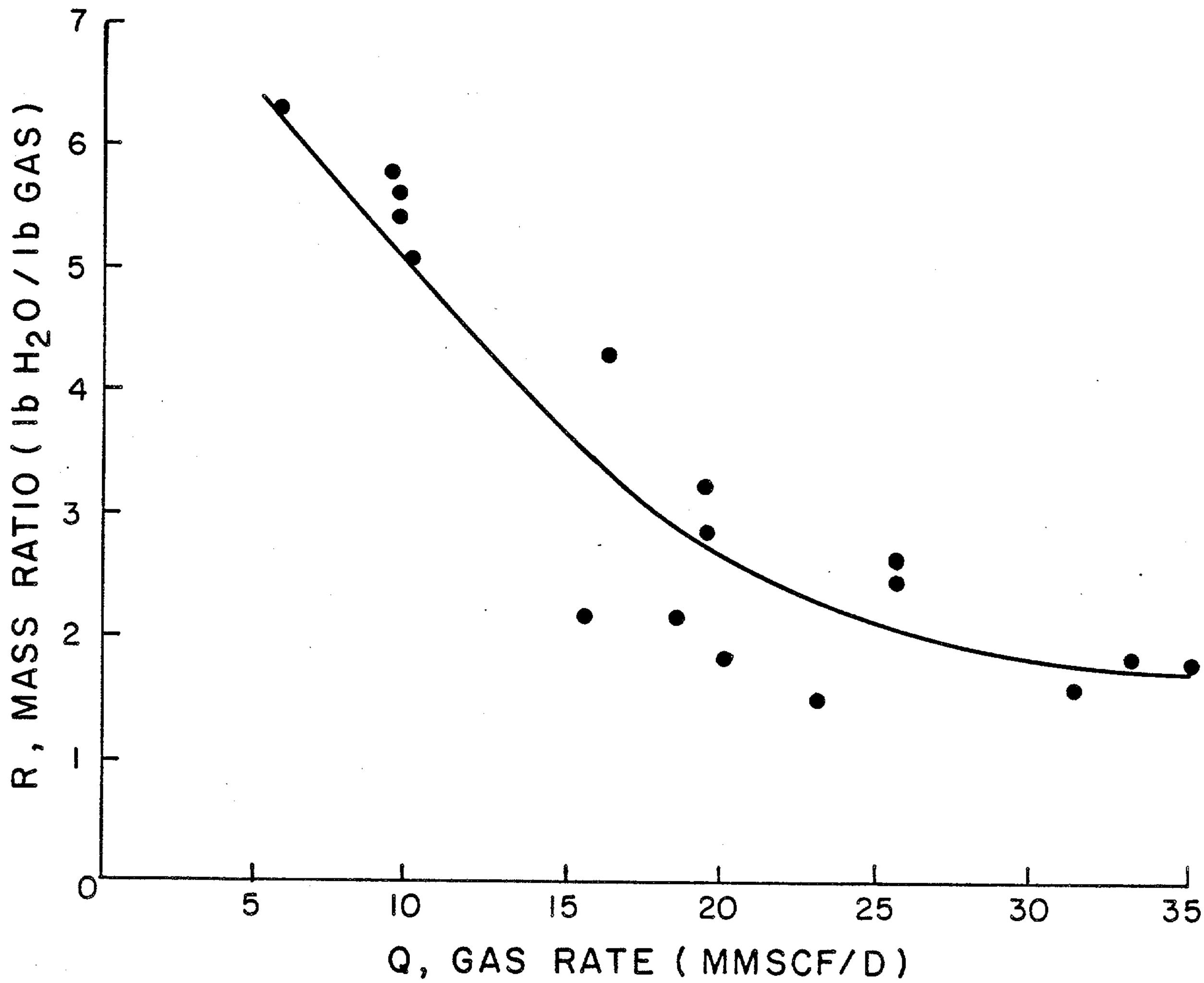

Figure 15. Summary of Data from Unobstructed Water Spray Tests

MMSCF/D, the mass ratios required were below 2. At lower gas rates, the required mass ratio increases to above 6 for a gas rate of 5 MMSCF/D. The reason for this significant increase in the required mass ratios at the factors affecting the combustion of a large jet diffusion flame are not understood. It is believed that the water spray is not as efficient at the lower gas rates because the flame does not have the necessary energy required to entrain a large fraction of the water droplets in the gas flow as a diluent. The extinguishment in this case would be more likely due to a "smothering" effect of the water spray. The higher mass ratios might also be attributed to the comparatively greater stability of the smaller flame versus the larger flame. The scatter of the data points can be attributed, for the most part, to the varying wind conditions. Cross wind effect can be difficult to quantify unless accurate measurements are made of wind speed and direction and no gusts are involved. The results of these tests were not tempered with a correction for cross wind mainly because of the wind gust condition, but its effect was evident throughout the tests. From observation, cross wind has an effect both on the flame plume and on the water spray patterns. The plume exhibits a decrease in stability to the point that it may be blown off if it is near the critical diameter for that gas rate (this was noted in table 2 of blowoff results). In addition to the flame stability changing with each gust of wind, the water spray is altered in the direction of the cross wind. The small droplets in the water spray appear to be affected the most because of their lesser momentum. These small droplets are believed to be the most important component of the spray since they are entrained into the gas flow and act to cool and dilute the flame. When these droplets are carried away from the base of the flame by wind, they cannot be involved in the entrainment process.

4.2.2 Obstructed Fires

The second group of tests studied were directed at simulating, to varying degrees, the effect of an obstruction on the efficiency of the water spray system. These tests were divided into two groups. The first series of tests were conducted with a 4 in. I-beam obstruction above the flame and the second series examined the effect of a 55 in. square platform over the flame.

The results of the 4 in. I-beam tests are given in table 4. The I-beam was placed 45 in. above the well exit with the flat side down. The data from table 4 are plotted in figure 16 with the mass ratio versus the gas rate. Note that the water requirements are increased almost two fold in the lower gas rate region, but the difference diminishes as the rate approaches 15 MMSCF/D. The higher gas rates were not performed because it was recognized that the maximum water rate could not extinguish any fires above 20 MMSCF/D with existing pump capabilities. The high water requirements for the lower rates indicates the difference a single I-beam can make. The increased difficulty of extinguishment that was observed in the I-beam obstruction tests was even more pronounced for the platform tests. The platform was very effective in deflecting the water spray outwards while, at the same time, increased mixing of air and gas occurred. The gas rate was varied from 2-20 MMCF/D using the maximum water rate and the only extinguishment occurred at a nominal gas

TABLE 4. Extinguishment Tests Conducted for a Flame Obstructed by a Single 4 in. I-Beam Placed 2 Ft. above the Flame

Run No.	Gas Flow Rate (MMSCF/Day)	Extinguishment Water Flow Rate (lb/min)	Gas Exit Pressure (psig)	Gas Temperature (°F)	Water-Gas Mass Ratio
1	13.1	2120	11	60	4.92
2	13.2	2130	17	60	4.90
3	7.2	2150	8	60	9.07
4	7.5	2180	8	60	8.84
5	5.7	2000	0	60	10.67
6	5.8	2150	3	60	11.27

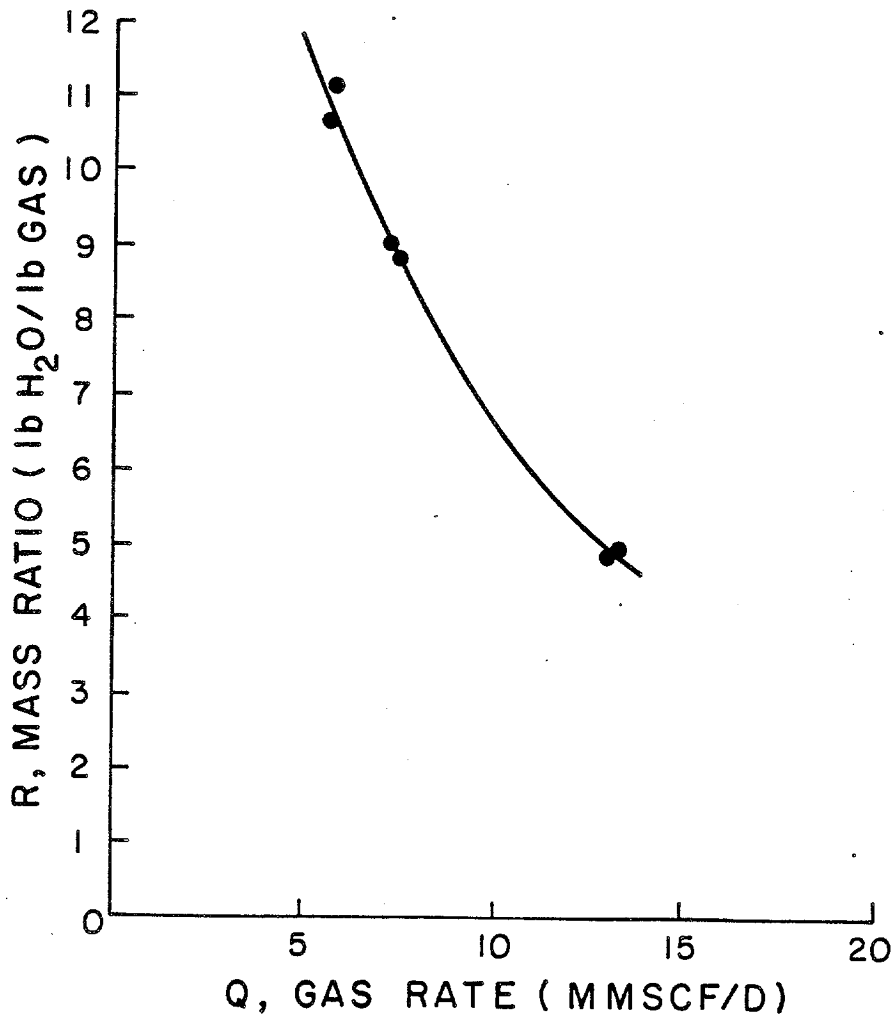

Figure 16. Summary of Extinguishment Tests with 4 inch I-Beam Installed

rate of 2 MMCF/D. This gives a mass ratio of 30. Lower mass ratios may have been possible for other spray arrangements and for higher gas flow rates. However, these initial results were discouraging.

A comparison of all the water spray data is illustrated in figure 17. This figure suggests that the effects of obstructions are more important at low gas flow rates.

In addition to the mass ratio data taken for the water spray system, several data points were recorded for radiation emitted by fires with and without water sprays. A representative strip chart record is illustrated in figure 18 and the data from several tests is recorded in table 5. These data points were only monitored for correlation with the previous work[1] done on water sprays. Nonetheless, the data indicate the beneficial cooling effect as a result of the water sprays.

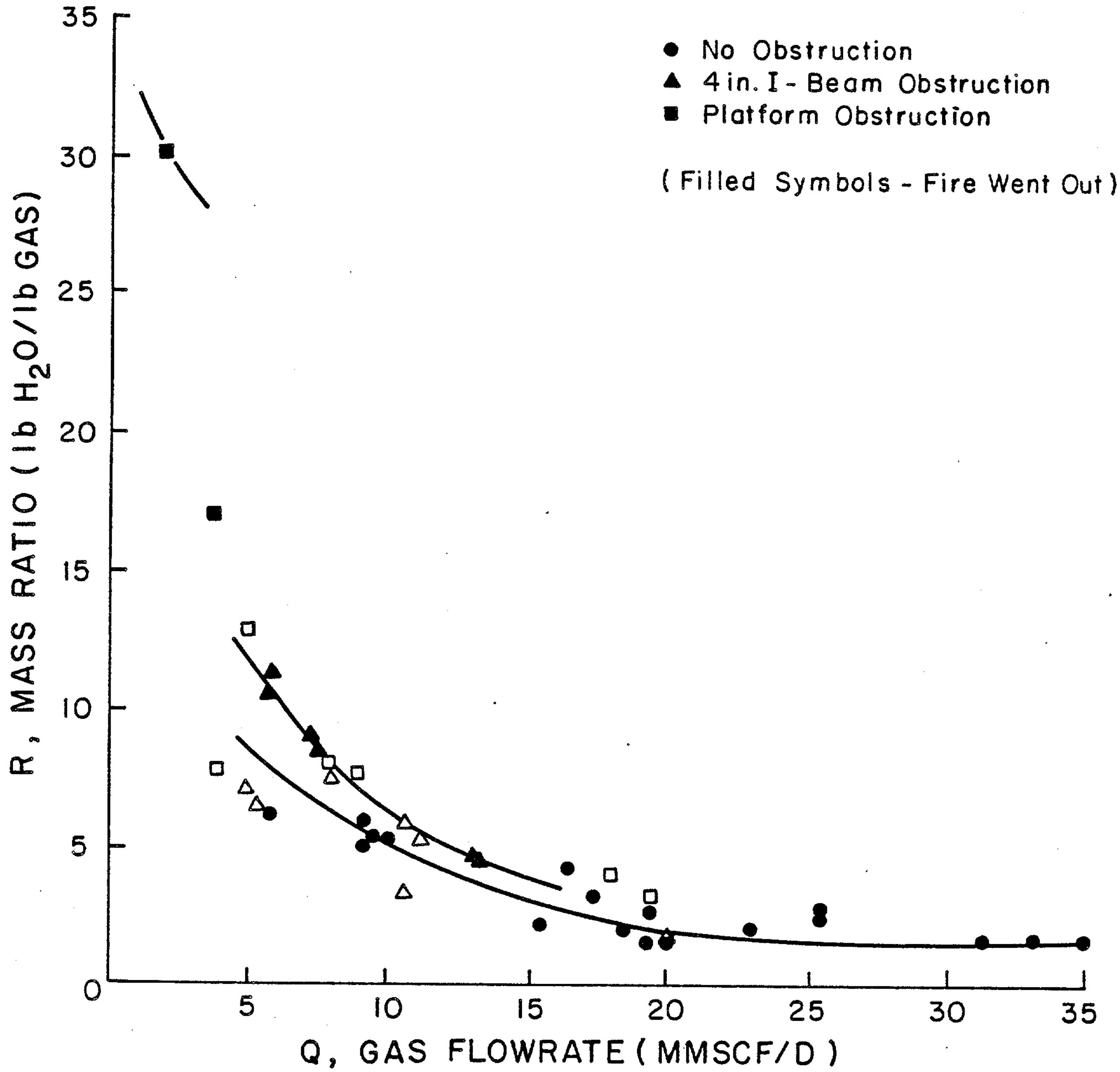

Figure 17. Summary of All Water Spray Tests for Both The Obstructed and Unobstructed Fires

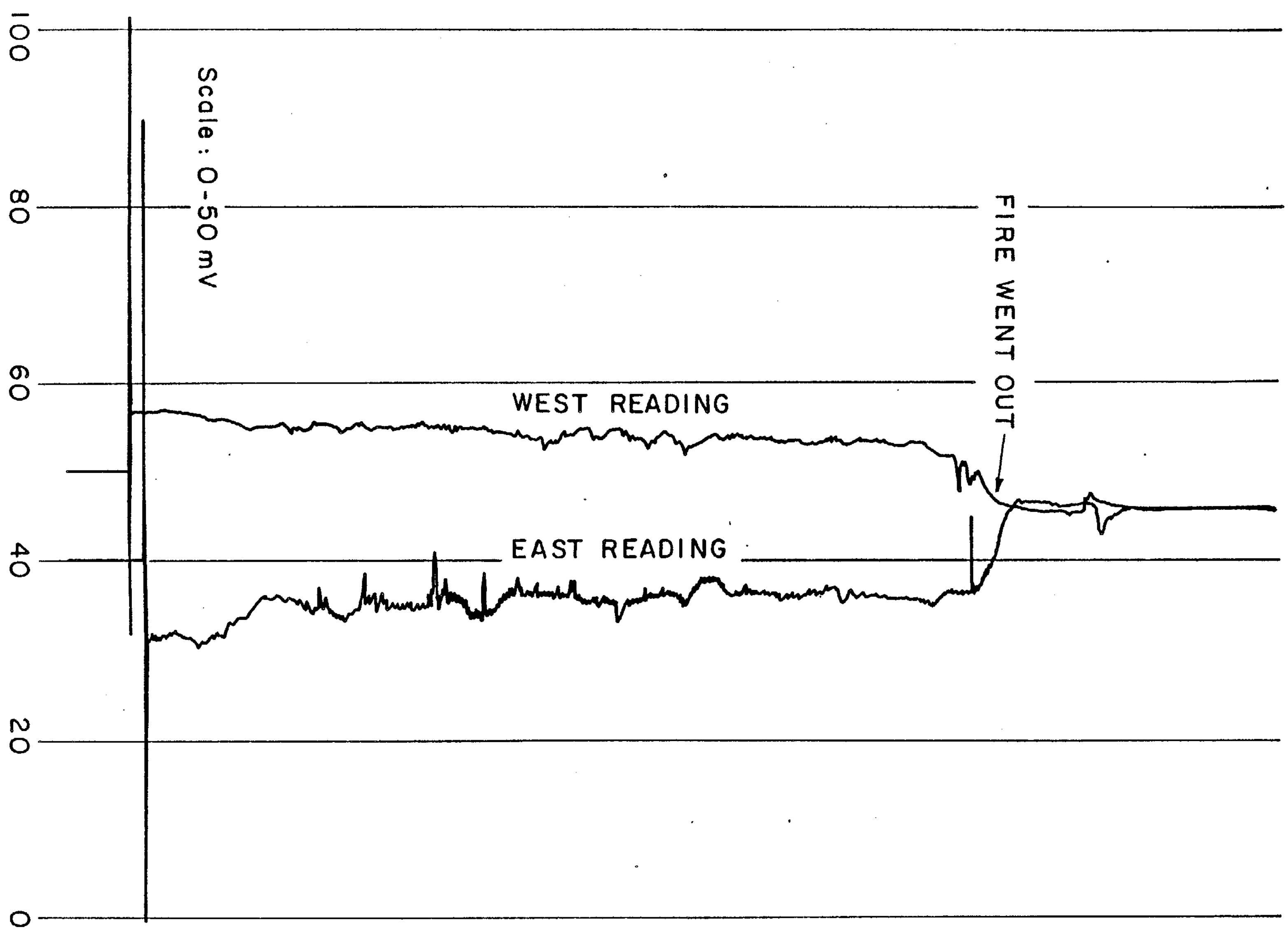

Figure 18. Typical Strip Chart Record for the Radiometer Readings of the Water Spray Tests

TABLE 5. Summary of Radiometer Measurements for the First Ten Unobstructed Fires

Radiant Heat Transmitter Readings

Date	Run No.	Wind Speed & Direction	Gas Rate MMSCF/D	East Reading w/m^2	West Reading w/m^2	Water Rate lb/min
7/11	1	0-5 SE	9.6	25.4	26.3	1100
7/11	2	5-10 SE	19.0	45.7	43.17	1960
7/11	3	5-10 SE	37.5	>234 (off scale)	236.9	350
7/11	4	10-15 SE	34.3	138.3	63.2	1200
7/11	5	10-15 SE	38.0	>254.2 (off scale)	>210.6 (off scale)	270
7/11	6	5-10 SE	22.5	147.5	121.09	100
7/11	7			off scale	off scale	
7/11	8			off scale	off scale	
7/11	9	5-10 SE	20.5	50.8	36.8	1150
7/11	10	10-15 SE	27.5	52.9	31.6	1750

5. CONCLUSIONS

As a result of the experimental test program conducted, the following conclusions can be drawn:

1. An unobstructed natural gas fire burning at a rate above 35 MMSCF/D can be extinguished for a water to natural gas ratio by weight of 1.8.

2. A natural gas fire with an obstruction above it requires more water for extinguishment than an unobstructed fire. The water requirements increase as the surface area of the obstruction increases.

3. Flame blow off, due to instability, was not possible for orifice diameters greater than 42 mm using natural gas but blow off does occur for smaller diameter orifices.

4. The radiative fraction can be significantly reduced by the use of water sprays up to the point of extinguishment.

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Appendix A

Composition of Natural Gas

Used in the Study

TABLE 6. Composition of Pipeline Gas

Gas Composition

Component	Mole Percent
C_1	0.14
C_2	2.60
C_3	92.06
iC_4	3.58
C_4	0.79
iC_5	0.20
C_5	0.16
C_6	0.11
C_7^+	0.06
N_2	0.11
CO_2	0.19
	100.00

Specific Gravity at 60°F 0.6230

Calculated BTU/cu. ft. @ 15.025 psia and 60°F
Dry Basis 1074
Wet Basis 1056

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The effect of obstructions in the gas flow on the ability of water sprays to extinguish simulated gas well blowout fires was examined using test fires with natural gas flow rates up to 35 MMSCF/D. This series of tests extends previous measurements of water spray extinguishment of simulated un-obstructed natural gas blowout fires adding obstructions that would almost certainly be present during accidents on actual platforms. It was found that the presence of obstructions in the gas flow increased the amount of water needed to extinguish the fire compared to an un-obstructed blowout fire. It is believed that an obstruction increases air/gas mixing while at the same time it decreases water/gas mixing.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

blowout fires; water sprays; extinguishment; offshore drilling

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